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SUMMARY REPORT TO

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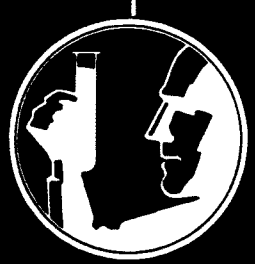
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



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ABSTRACT

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A mail survey of 605 metal-related industries was conducted under NASA Contract No. NAS 8-5201 to determine the present role of magnetic-pulse forming (MPF) in industry, to evaluate its future prospects, and to estimate the feasibility of establishing a NASA-sponsored facility in an independent laboratory to aid industry in exploiting the potential benefits of the forming method. The 192 replies received (a 31.8% response) were evaluated on the basis of the total response, the response divided into ten industry classifications, and the response divided according to four different degrees of previous acquaintance with the process. These evaluations resulted in the conclusions that the MPF process has a promising potential that is not being realized by American industry, that more information on basic practical parameters is needed before industry can adequately evaluate the process in comparison with conventional forming methods, and that the establishment of an experimental facility in an independent laboratory would be justified.

AUTHOR

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A STUDY OF THE INDUSTRIAL APPLICATIONS OF MAGNETIC-PULSE METAL FORMING

INTRODUCTION

The purpose of this study was to determine the present role of magnetic-pulse forming in industry, to evaluate its future prospects for supplementing or replacing other forming methods, and to estimate the feasibility of establishing a NASA-sponsored facility to aid industry in exploiting the potential of the method by providing pertinent technological and cost information. The study was initiated as a part of the recently established NASA policy (12, 13)[1] of disseminating, for the benefit of private industry and the general public, technological innovations developed in their space programs.

Magnetic-pulse forming is a new process in the field of high-energy-rate forming methods. The use of high-energy-rate methods is increasing because they often have advantages over conventional methods in the fabrication of difficult shapes and large sizes, particularly when low-quantity rates of production are involved. Also, many materials that resist deformation by conventional processes can be deformed successfully by one or more of the high-energy-rate processes.

Although industrial development work has resulted in the use of magnetic-pulse forming for small parts made from thin-walled tubing or thin sheet stock, mostly with aluminum or copper alloys, (6, 8, 10) the work at Marshall Space Flight Center has shown that the process is capable of application to much larger configurations (9, 11). Experience with the process at MSFC has indicated that many promising industrial applications have not been pursued (11). In addition, the number of inquiries received from industry has indicated that interest in the process might be quite high if enough information were made available to allow accurate comparisons to be made with conventional processes. Since MSFC cannot interrupt their space research to compile and publish the needed information, the survey reported herein was made to determine the need for the establishment of an independent research facility to adapt their advanced findings to industrial use. It was envisioned that such a facility would be sponsored by NASA only to the extent of building the essential equipment and determining preliminary basic information. Further development for specific uses would then be accomplished from private industrial funds, either in jointly sponsored or individually sponsored programs.

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[1] Numbers in parentheses refer to the Bibliography.

PROCEDURE

A brief literature survey was made to determine the amount of information that was available from published sources, and to aid in the design of a letter, information sheet, and questionnaire that were subsequently mailed to metal-working companies. Because of the usual reluctance on the part of manufacturers to answer questionnaires that do not involve sales opportunities, and because information was being sought on production rates and costs that most manufacturers do not release, much thought was given to the design of the questionnaire and the auxiliary material prepared to accompany it. By carefully planning the questions and reducing the size of the lettering, the entire questionnaire was contained on a single 8-1/2 x 11 - in. page. The questions were arranged so that all of the desired information could be supplied by check marks, numbers, or single-word answers. The recipient was invited to submit any supplementary information he wished to supply in whatever form was most convenient to him.

A letter stating the purpose of the survey, the manner in which it was to be conducted, and the instructions required for supplying the answers was written to accompany the questionnaire. In addition, an information sheet that briefly described the principles of magnetic-pulse forming and suggested some typical prospective applications to stimulate further ideas was included in the mailing. Copies of the letter, questionnaire, and information sheet are included in the Appendix of this report.

A list of more than 600 manufacturers was compiled, mostly from information obtained from the Thomas Register and the Dun and Bradstreet Million Dollar Directory. Mailings to these companies were addressed to the attention of the names of appropriate company officers or directors if this information was available. The other mailings were addressed to the attention of either the President or General Manager. In addition to the mailings, several personal interviews were made by telephone and visits, mostly in the Birmingham area.

For evaluation purposes the companies to which the questionnaire was mailed were divided into ten different categories of manufacturing interest. Attempts were made to classify the companies according to the Standard Industrial Classification Manual of the United States Office of Statistical Standards. This classification system was found to be inappropriate because the individual four-digit classifications were too detailed and the group two-digit classifications were too broad to successfully arrange companies in groups of similar interests in manufacturing techniques. Therefore the classification was made in accordance with the following scheme of manufacturing interests. Examples of the types of products included in each classification are listed after each heading. A small

number of manufacturers of nonmetallic products were included because many such products require metal reinforcements, connections, or fittings that must be formed and attached to the parts. Also, it was surmised that some manufacturers might wish to consider MPF from the standpoint of its possible application for forming and sealing metal containers.

1. Sheet Metal Configurations - Includes manufacturers of shelves, large stampings, signs, office and laboratory furniture, metal booths, metal buildings, baking pans, spinnings, textured sheets, antennas, dust collectors, filters, luggage, doors and trim, boats, lighting fixtures, laboratory ovens, perforated sheets, etc.

2. Small Machines and Instruments - Includes manufacturers of office machines, computers, pneumatic cylinders, small arms, transducers, small motors, relays, solenoids, switches, servos, spray guns, clocks and timers, pumps, cable harness, vacuum cleaners, small household appliances, etc.

3. Small Stampings and Jewelry - Includes manufacturers of eyelet parts, fasteners, hardware, tableware, zippers, bearing races, name plates, badges, buttons, etc.

4. Tubing Configurations - Includes manufacturers of shipping drums, musical instruments, round ductwork, fuel tubes, chairs, valves, fittings, radiators, bellows, hose, etc.

5. Large Machines - Includes manufacturers of conveyors, elevators, pressure vessels, barges, cranes, automobiles, tractors, machine tools, industrial furnaces, large appliances, motorcycles, ships, etc.

6. Air and Space Vehicles - Includes manufacturers of airplanes and accessories, rocket cases, missiles, auxiliary space equipment, etc.

7. Primary Metals - Includes producers of bar stock, plate, sheet, powdered metals, etc.

8. Unclassified - Includes laboratories, engineering companies, and unidentified returned questionnaires.

9. Plate and Structural Configurations - Includes manufacturers of plumbing wares, heavy cookware, large drums, water heaters, wheels, etc.

10. Nonmetallic Products - Includes manufacturers of nonmetallic hose, abrasives, adhesives, graphic products, packing, gaskets, paints, nonmetallic powders, etc.

The results were evaluated on the basis of the total response, the response distributed according to industry classification, and the response distributed according to the extent of previous acquaintance with the process. Other data, consisting of cost information, supplementary comments made by the respondents, and impressions gained from personal interviews, were useful only for aiding in the interpretation of the results.

RESULTS

Results Based on Total Response

The distribution of the total of 605 mailings by industry classification is shown by a bar chart in Figure 1. Both the number of mailings in each classification and the distribution by percentage are shown. The industry classifications are arranged in descending order of quantity of mailings, and this order has been repeated throughout the remainder of this report.

Figure 2 shows the response classified on four different bases. The total response from the 605 mailings was 192, or 31.8%. Since a 10% return from this type of questionnaire would have been considered satisfactory, the return amounting to almost one third of the mailings is judged to be a good response. The total return consisted 77.1% of questionnaires only, 14.6% of questionnaires accompanied by a letter or brochure, and 8.3% of letters only. The breakdown of the returns by industry classification shows that the response followed roughly the same order as the distribution of mailings. The percentage of the total response from manufacturers of SMALL MACHINES AND INSTRUMENTS was within 1% of the percentage of mailings for this category. On a percentage basis the response from manufacturers of SHEET METAL CONFIGURATIONS and manufacturers of SMALL STAMPINGS AND JEWELRY was considerably less than the distribution of the mailings. Therefore, the percentage return from the other manufacturing classifications was slightly higher than the mailing distribution.

The lower block in Figure 2 shows the extent of response to the various questions on the questionnaire. More than 90% of the respondents answered the questions relating to their previous acquaintance with the process, the extent of the interest of their company or division in the process, and their opinion of the benefits to be derived from the proposed experimental facility. Cost information on parts that might be advantageously formed by the process was supplied by 20.4% of the respondents and another 18.2% supplied information on parts only. More than two thirds of the respondents requested to be informed of the results of the survey.

Figure 3 shows the extent of previous acquaintance with the process reported by the 176 respondents that answered this question. The results are

Figure 1.

DISTRIBUTION OF MAILINGS BY INDUSTRY CLASSIFICATION

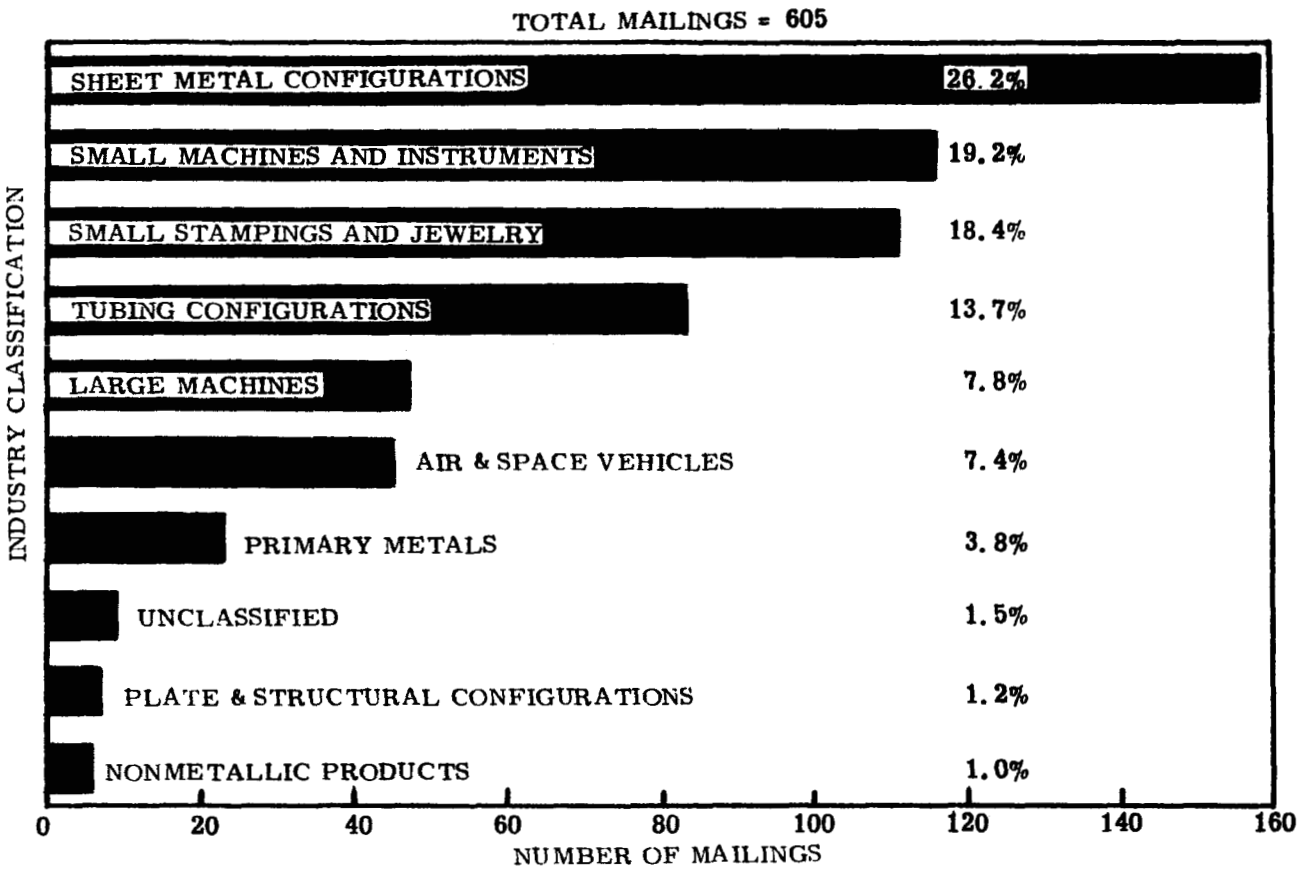


Figure 2.

DISTRIBUTION OF TOTAL RESPONSE

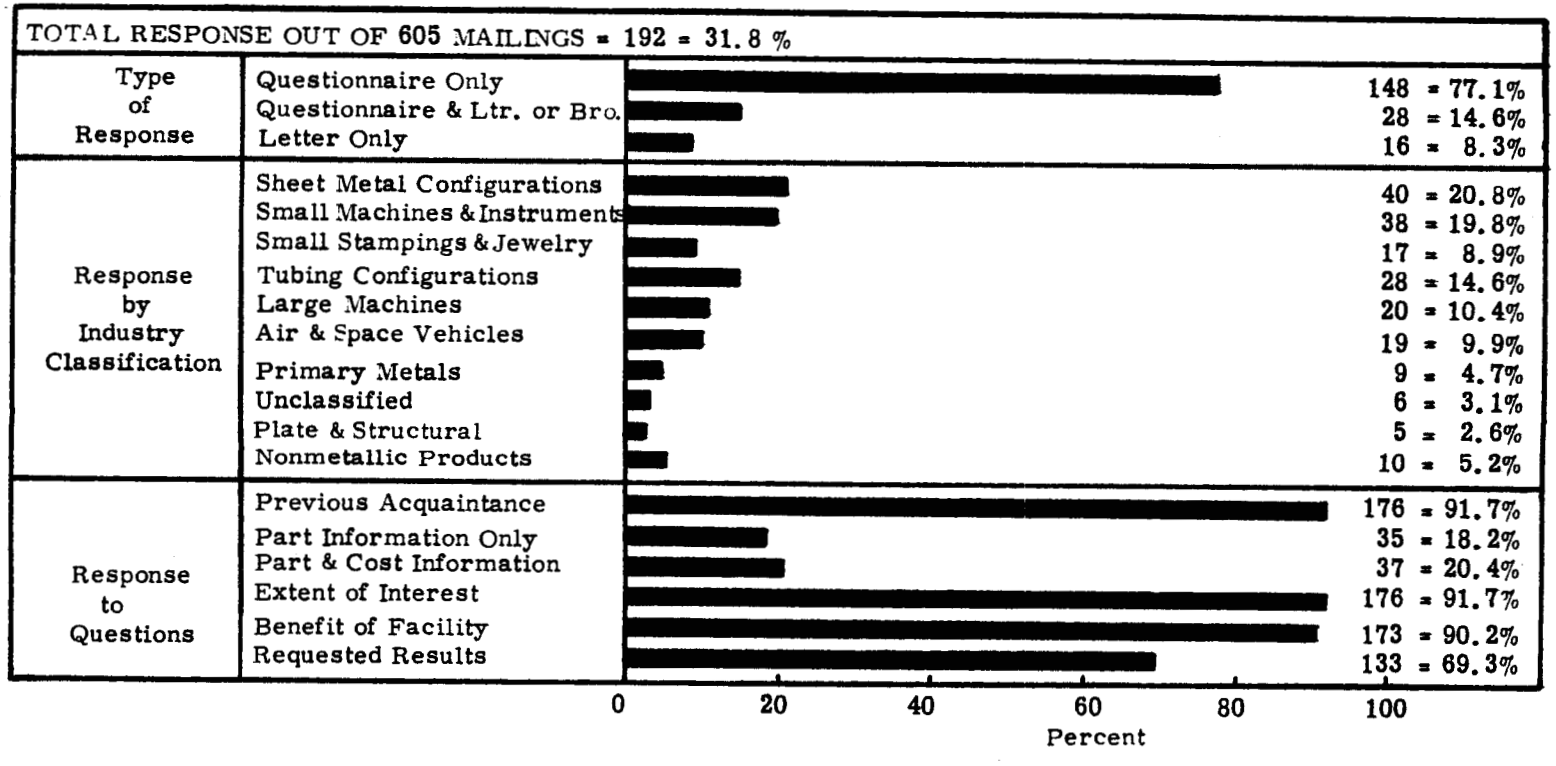
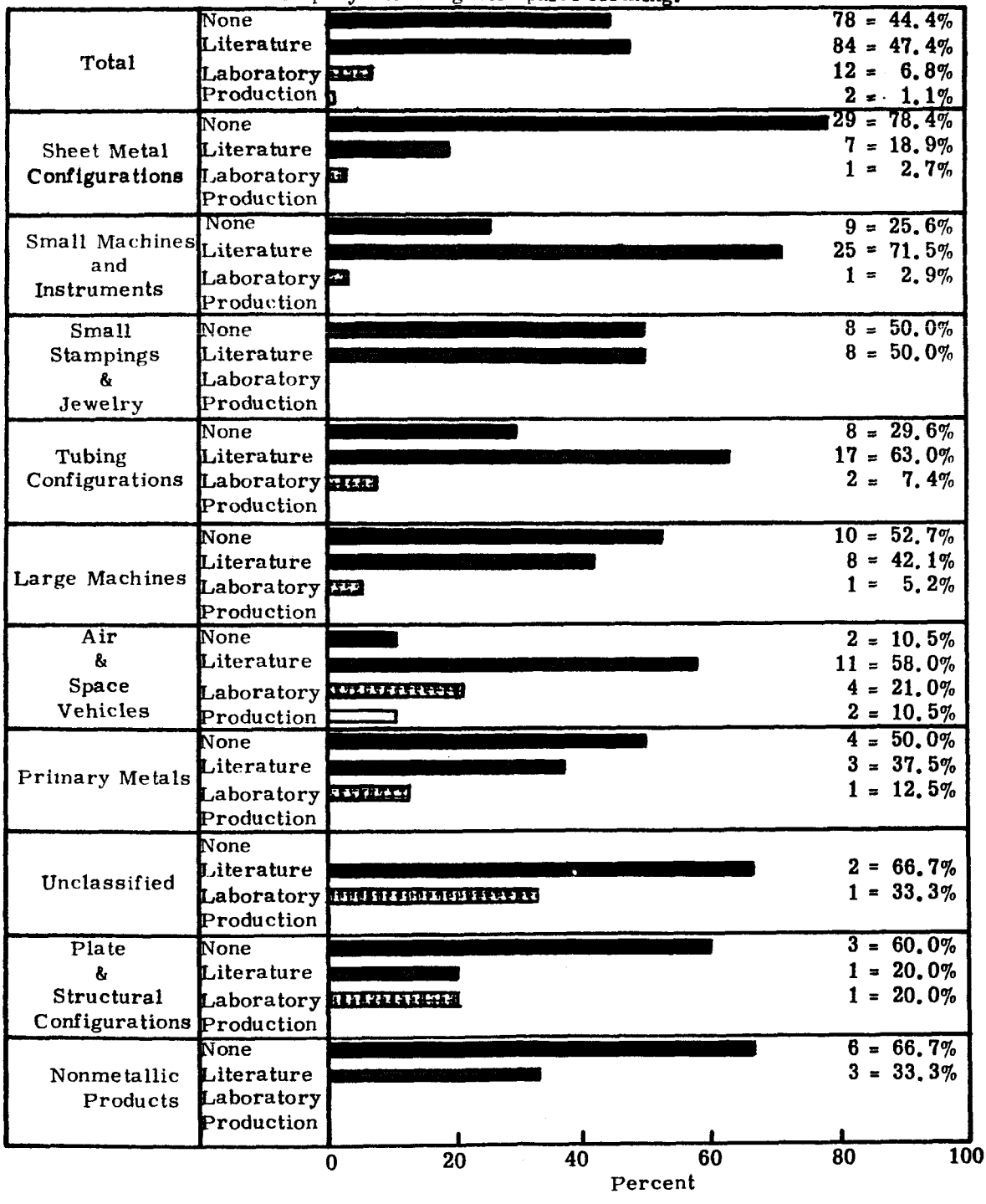


Figure 3.

DISTRIBUTION OF ANSWERS TO QUESTION 2 BY INDUSTRY CLASSIFICATION

Question 2: What has been the previous acquaintance of your division or company with magnetic-pulse forming.



shown both on the basis of the total returns and as divided into the industrial classifications. On the basis of total returns more than 90% of the respondents reported that they had not been previously acquainted with the process or had only read of it in the literature. Only two companies reported any production experience, and they were both from the AIR AND SPACE VEHICLE classification. A meager amount of laboratory experience was reported by respondents from eight of the industry classifications.

Results Based on Industry Classifications

The results from the answers to questions 5 and 6 of the questionnaire, based on the industry classifications as compared to the total response, are shown in Figures 4 and 5 respectively. Question 5 asked: "To what extent do you think your company or division would be interested in exploring the usefulness of magnetic-pulse forming for your operations:" and requested the respondent indicate either "considerable," "moderate," or "negligible" interest. Figure 4 shows that in the total response "moderate" interest dominates and "negligible" interest is prevalent over "considerable" interest. The same pattern of "moderate" to "negligible" interest is indicated by the majority of the industry classifications. Two of the exceptions to this pattern were the classifications TUBING CONFIGURATIONS and AIR AND SPACE VEHICLES. "Moderate" interest dominated among the manufacturers of TUBING CONFIGURATIONS but all of the remainder in this classification indicated "considerable" interest. "Considerable" interest was dominant among the manufacturers of AIR AND SPACE VEHICLES and "moderate" interest was indicated by the majority of the remainder in that classification. Three classifications, PRIMARY METALS, UNCLASSIFIED, and NONMETALLIC PRODUCTS, show a high percentage of "negligible" interest. In the UNCLASSIFIED group, however, the remainder indicated "considerable" interest.

The numerical values in Figure 4 show that less than ten returns are represented in each of the bottom four classifications in the figure; that is, PRIMARY METALS, UNCLASSIFIED, PLATE AND STRUCTURAL CONFIGURATIONS, and NONMETALLIC PRODUCTS. Therefore, it may be questioned whether the sample size in these four classifications is large enough to be representative.

Figure 4.

DISTRIBUTION OF ANSWERS TO QUESTION 5 BY INDUSTRY CLASSIFICATION

Question 5: To what extent do you think your division or company would be interested in exploring the usefulness of magnetic-pulse forming for your operations.

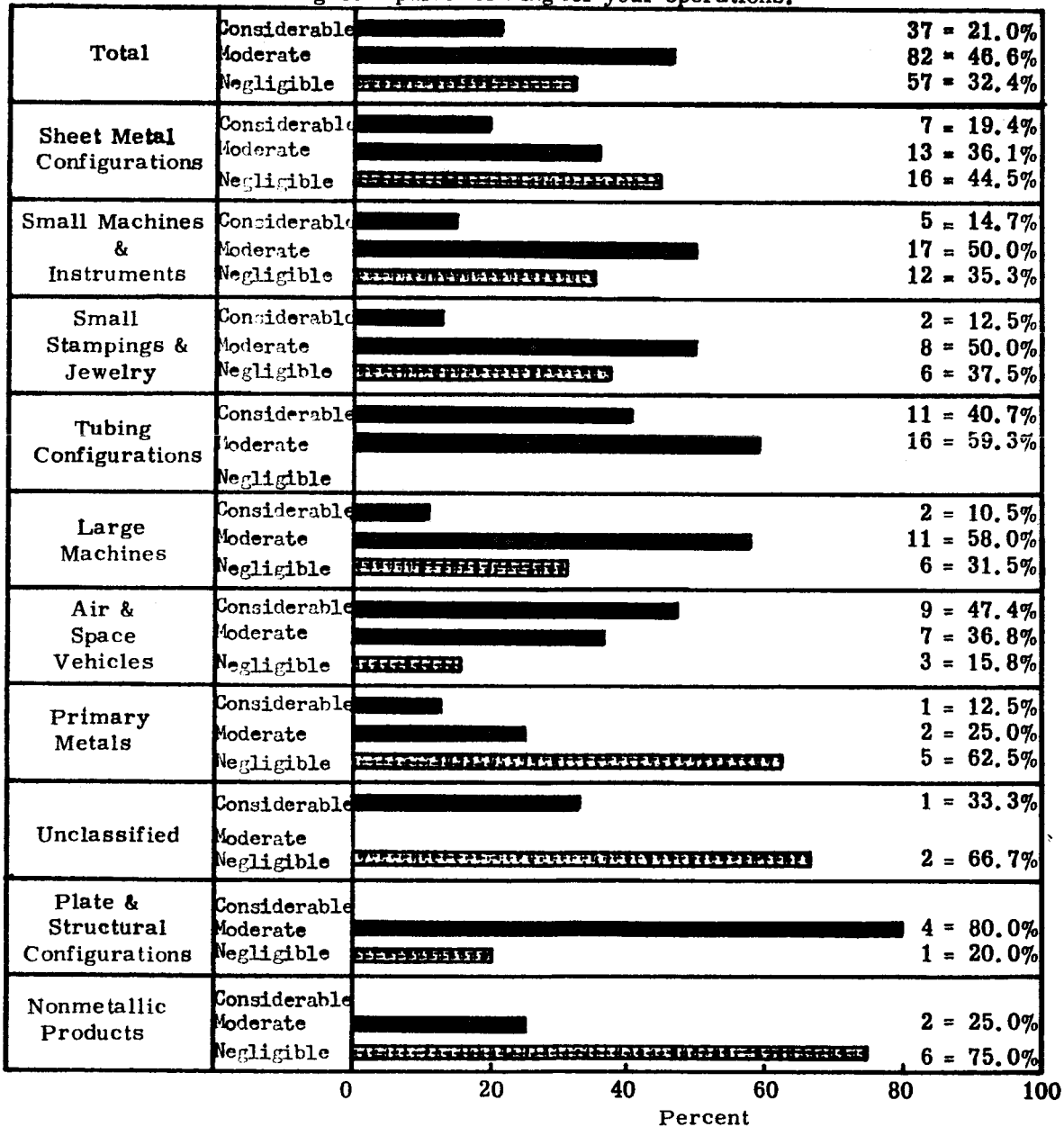


Figure 5 shows the corresponding distribution of answers to question 6, which asked: "Do you think your company or division would derive benefits from the establishment of an NASA-sponsored experimental facility?" Respondents were requested to answer the question by indicating "yes," "uncertain," or "no." In the total response the "uncertain" replies outnumbered the other two and, of these, the "yes" replies slightly outnumbered the "no" replies. In the industry classifications, the replies from the manufacturers of LARGE MACHINES were similarly distributed. In SMALL MACHINES AND INSTRUMENTS and UNCLASSIFIED the replies other than "uncertain" were evenly distributed between "yes" and "no." In four of the classifications, SMALL STAMPINGS AND JEWELRY, PRIMARY METALS, PLATE AND STRUCTURAL CONFIGURATIONS, and NONMETALLIC PRODUCTS, most of the replies were "uncertain" but the number of "no" replies exceeded the number of "yes" replies. The distribution under SHEET METAL CONFIGURATIONS is similar except that the "uncertain" and "no" replies were equal in number. A majority of "yes" replies were received in the TUBING CONFIGURATIONS and AIR AND SPACE VEHICLES classifications.

The data from Figures 4 and 5 are generalized in Figure 6, which separates the industry classifications into various boxes denoting the extent of interest in the process and the extent that the companies would benefit from the establishment of the proposed experimental facility. These generalizations are merely indicative of the degree of interest of the majority of companies within the different classifications. As shown in Figures 4 and 5 a significant minority, not represented in Figure 6, may have considerable interest even though a majority do not. Entries were made in the "considerable," "yes," "negligible," and "no" boxes only if the returns had a clear majority (greater than 50%) in those categories. The entries in the other four boxes depended upon which side of "moderate" or "uncertain" received the most tallies. It is shown in the column for extent of interest that none of the classifications had a majority with "considerable" interest whereas two classifications, PRIMARY METALS and NONMETALLIC PRODUCTS, are in the "negligible" box. The two classifications in which most activity in magnetic-pulse forming would be expected, TUBING CONFIGURATIONS and AIR AND SPACE VEHICLES, show "considerable to moderate" interest. All of the remaining classifications, including TOTAL RESPONSE, indicated "moderate to negligible" interest.

Comparison of the two columns in Figure 6 indicate a trend toward greater interest in an experimental facility than in the process itself at present. The two classifications that were in the "considerable to moderate" box had a majority of "yes" replies to the facility question. Similarly, TOTAL RESPONSE and LARGE MACHINES from the "moderate to Negligible" box are

Figure 5.

DISTRIBUTION OF ANSWERS TO QUESTION 6 BY INDUSTRY CLASSIFICATION

Question 6: Do you think your division or company would derive benefits from the establishment of an NASA-sponsored experimental facility?

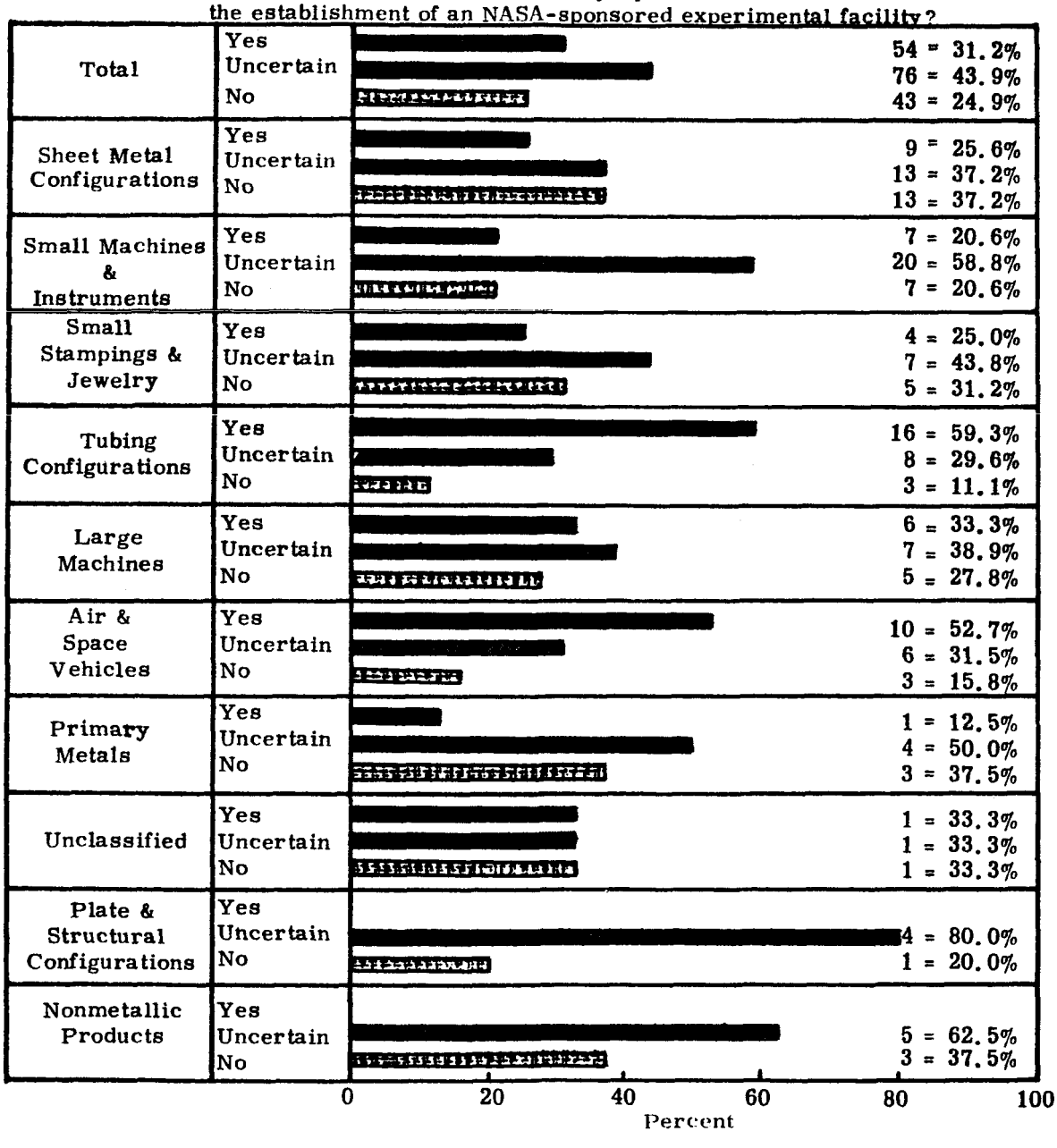


Figure 6.

SUMMARY OF RESULTS FROM QUESTIONS 5 AND 6 BASED ON INDUSTRY CLASSIFICATION

Extent of Interest	Would Benefit from Facility
Considerable	Yes
	Tubing Configurations Air and Space Vehicles
Considerable to Moderate	Yes to Uncertain
Tubing Configurations Air and Space Vehicles	Total Response Small Machines and Instruments* Large Machines Unclassified*
Moderate to Negligible	Uncertain to No
Total Response Sheet Metal Configurations Small Machines and Instruments Small Stampings and Jewelry Large Machines Unclassified Plate and Structural Configurations	Small Machines and Instruments* Unclassified* Sheet Metal Configurations Small Stampings and Jewelry Primary Metals Plate and Structural Configurations Nonmetallic Products
Negligible	No
Primary Metals Nonmetallic Products	

* Tied results were placed in both boxes.

located in the "yes to uncertain" box. With the exception of the two classifications with tied results, all of the remainder are in the "uncertain to no" box. None of the classifications had a majority of "no" answers. These results indicate that the relatively low level of interest of many companies in most of the industry classifications is caused in part by a lack of the information necessary to adequately evaluate MPF, and that most of the classifications reflect this lack of information by exhibiting a relatively higher interest in the establishment of the experimental facility.

Results Based on Previous Acquaintance with MPF

Figures 7 and 8 illustrate the distribution of the responses to questions 5 and 6 with respect to the previous acquaintance of the respondents with MPF. The total responses, shown in these figures for comparative purposes, are the same as those plotted in Figures 4 and 5. Figure 7 shows, as might be expected, that interest in the process is greatest among those that have the greatest familiarity with the process. The distribution of replies to question 6, shown in Figure 8, is much more diverse. The generalization of these results, shown in Figure 9, indicates that, on the basis of previous acquaintance, a need for the experimental facility exists similar to that indicated in Figure 6 on the basis of industry classifications. However, this need is not indicated as strongly as it was on the basis of industry classification. For example, the respondents with "laboratory" experience are in opposition to the trend established by the other categories in that the expectation of benefits from the experimental facility shows a lower level of enthusiasm than is shown for interest in the process.

Cost Information

Although cost information was supplied by a gratifyingly large number of respondents (20.4% as shown in Figure 2), little of it was supplied in sufficient detail to make reliable cost comparisons. For example, several products were suggested for which MPF might be expected to eliminate or reduce the cost of multiple conventional production operations; yet, cost figures were supplied for only one operation. Also, widely varying production costs for similar operations were reported by different manufacturers, indicating that the costs were not figured on the same basis. Many manufacturers listed only part numbers or failed to provide any indication of the dimensions of the suggested part.

Figure 7.

DISTRIBUTION OF ANSWERS TO QUESTION 5 BY EXTENT OF PREVIOUS ACQUAINTANCE

Question 5: To what extent do you think your division or company would be interested in exploring the usefulness of magnetic-pulse forming for your operations?

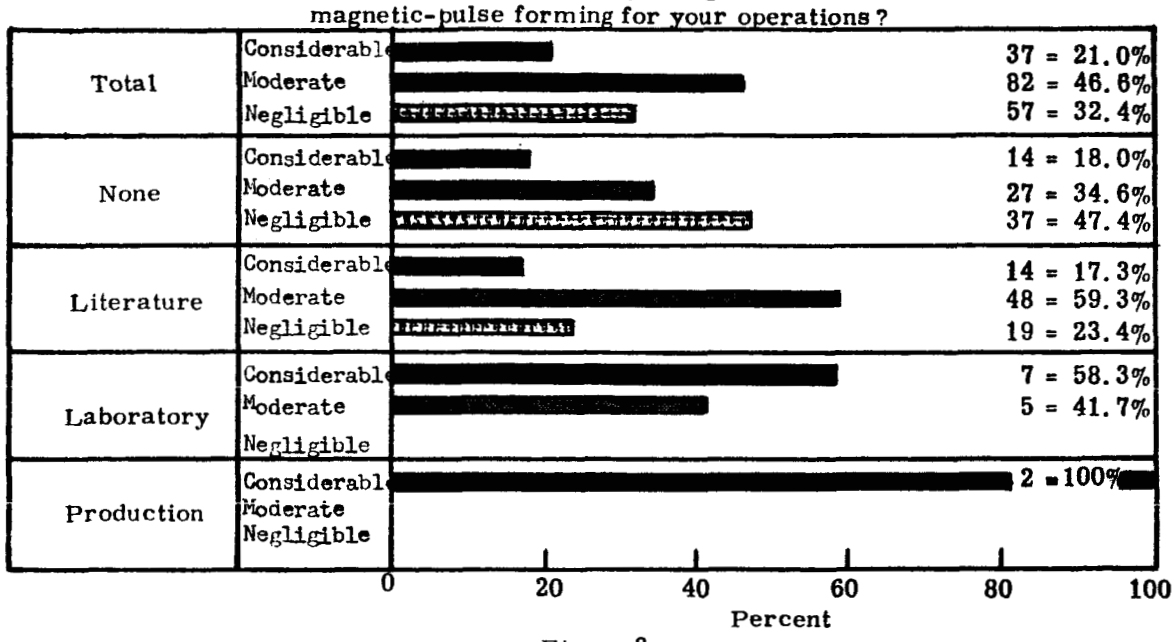


Figure 8.

DISTRIBUTION OF ANSWERS TO QUESTION 6 BY EXTENT OF PREVIOUS ACQUAINTANCE

Question 6: Do you think your division or company would derive benefits from the establishment of an NASA-sponsored experimental facility?

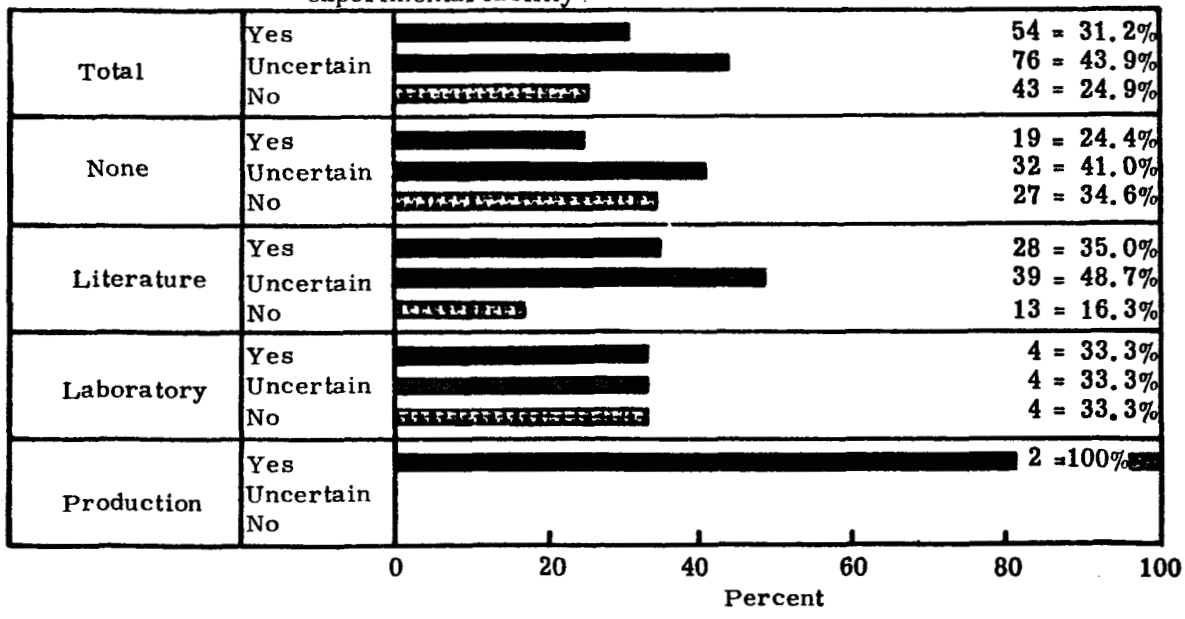


Figure 9.

SUMMARY OF RESULTS FROM QUESTIONS 5 AND 6 BASED ON EXTENT OF PREVIOUS ACQUAINTANCE

Extent of Interest	Would Benefit from Facility
Considerable Laboratory Production	Yes Production
Considerable to Moderate	Yes to Uncertain Total Response Literature Laboratory*
Moderate to Negligible Total Response None Literature	Uncertain to No None Laboratory*
Negligible	No

* Tied results were placed in both boxes.

One respondent reported the result of a value analysis on a threaded coupling for which MPF is expected to reduce the total direct production cost from $7.35 to $1.10 per piece. It is likely that the production cost of many machined parts could be reduced by MPF if a similar analysis were made. Unfortunately, this type of analysis could not be made with the inadequate information submitted. A summary table containing most of the cost data that was submitted is presented in the Appendix.

Supplementary Comments

More than 50 respondents made supplementary comments, written either on the questionnaire or in a separate letter. Most of the comments pertained only to the process itself but fourteen replies contained opinions about the establishment of the proposed experimental facility. Seven of these fourteen replies were judged to be unfavorable comments although two of them were worded in a manner to express curiosity rather than disapproval. The remaining seven of these replies were judged to express favorable comment. All of the replies that contained only comments pertaining to the process were considered to be neutral on the facility question except as expressed by the answers checked on the questionnaire.

It was not possible to devise a method for summarizing the supplementary comments. Therefore, pertinent exerpts are quoted in the following numbered paragraphs. The seven unfavorable comments are listed first, then the favorable comments, and finally the neutral comments. Each comment is preceded by information giving the industry classification to which the company was assigned, the previous acquaintance with the process, the answer to question 5 (interest in the process), and the answer to question 6 (on the benefits to be derived from the facility). Some of the quoted comments are followed by pertinent remarks made by the author of this report. All references to individual or company names have been omitted in order to preserve the anonymity of the respondents.

Unfavorable Comments:

1. Classification: Sheet Metal Configurations; Acquaintance: literature; Interest: moderate; Facility: no. Comment: (referring to the facility) "There are ample private facilities to perform this function if it has commercial possibilities. They can do it cheaper, quicker, and better."

2. Classification: Small Machines and Instruments; Acquaintance: laboratory; Interest: moderate; Facility: no. Comment: (referring to the facility) "I feel this work should be done by the manufacturers of the magnetic-pulse equipment."

3. Classification: Tubing Configurations; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "Your questionnaire to determine information for the government in its quest for backing for setting up a facility for parallel research with existing private industry has been referred to me. We do not use this technique in our phase of the business, although we have been in touch with (equipment manufacturer). We therefore decline to answer the questionnaire furnished."

4. Classification: Tubing Configurations; Acquaintance: laboratory; Interest: considerable; Facility: uncertain. Comment: "We are interested in the possibilities for magnetic-pulse forming in our business and have been co-operating with (equipment manufacturer) for nearly a year. Preliminary work done to date has caused us to undertake a further program which is just now beginning. We will be very much interested in learning why your Institute is making this survey, apparently relative to your contract with NASA as, it is our impression that (equipment manufacturer) and others are quite active in research and development directed toward industrial applications and commercial manufacturing practices." (Remarks: This letter was answered by Southern Research Institute to give further explanation on the reasons for the survey.)

5. Classification: Air and Space Vehicles; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: "I wish to qualify any impression which could be gained from our reply indicating approval of government sponsored research of this type. There are certainly many areas where government sponsored research is necessary in the interest of national defense and of benefit to industry as a whole. In this particular area however, we are dealing with an existing piece of equipment and attempting to develop its application through a government funded program. You are doubtless aware that several companies are working in this same area with their own funds. The developments made by several companies will undoubtedly uncover more application for this process than a single research group would in the same period of time. It seems to me that a government funded contract such as you propose would only tend to discourage further privately funded research. The advantages of such a program appear doubtful." (Remarks: This letter was answered to give further explanation of the reasons for the program and to express the opinion that the proposed determination of basic information would foster, rather than discourage, privately funded research.)

6. Classification: Nonmetallic Products; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: "We are curious about the relationship of a proposed NASA magnetic-pulse application facility to the promotional efforts of (equipment manufacturer). Representatives of the latter firm have previously discussed the (named) machine with us." (Remarks:

This letter was answered to explain more completely the reasons for the program and to emphasize that the program had no relationship to the equipment or process developments of any company.)

7. Classification: Nonmetallic Products; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "It would be my thought that you are to be criticized for sending this questionnaire to us. I don't know whether your contract with NASA is on a time-plus basis but certainly the simplest research would have shown you that (Company Name) manufactures nothing but paints and other coatings. As a tax payer, I object." (Remarks: This letter was answered to give a more complete explanation of the program and to explain how this company was chosen for participation in the survey. Several examples were given to show that a paint manufacturer might have interest in MPF).

Favorable Comments:

1. Classification: Small Machines and Instruments; Acquaintance: literature; Interest: negligible; Facility: uncertain. Comment: "Thank you for your reply concerning NASA space-age research information. Whenever the program is instituted, we would be interested in being on the mailing list."

2. Classification: Tubing Configurations; Acquaintance: none; Interest: considerable; Facility: yes. Comment: "Your letter has created such interest here, that we would like to have any additional information that is available on magnetic-pulse forming. We are in the (product) manufacturing business and do a considerable amount of swedging and dye forming of tubular parts, and this process could be a revelation to our business. Anything that you may forward to us would certainly be of interest." (Remarks: Literature references and the name of a nearby equipment manufacturer were sent in answer to this letter.)

3. Classification: Tubing Configurations; Acquaintance: literature; Interest: considerable; Facility: yes. Comment: "We have been very much interested in the developments (of MPF) and are attaching our answer to your questionnaire. We would be quite willing to comment further or to work with you in any way that we may. I am attaching a copy of our publication which briefly describes all of the products that we make. As you can see, we have many applications for magnetic-pulse forming. Thank you for contacting us and we will be interested in any further word that we may have from you."

4. Classification: Large Machines; Acquaintance: literature; Interest: moderate; Facility: yes. Comment: "Our present knowledge of Magnetic-Pulse Forming is quite limited, however we do believe that the process has possibilities depending upon the suitable development of an adequate initial power source. From what we have heard at seminars and have read, it is apparent that the present primary power source is extremely costly and has a very limited life. Without a doubt Industry and the forming field would benefit greatly from NASA experiments, and since (writer's company name) is in the forming field we would be interested in following the project. If there is any way in which we could be of assistance to your group in this program please advise, and we would like to have information on the results of your survey."

5. Classification: Large Machines; Acquaintance: none; Interest: considerable; Facility: yes. Comment: (Company name) "has 12 operating divisions and therefore makes a wide range of equipment. We at present do not have any operations using magnetic-pulse forming but we are very interested in following this development, therefore, would greatly appreciate being kept currently informed on any work that your organization carries out along these lines."

6. Classification: Air and Space Vehicles; Acquaintance: literature; Interest: considerable; Facility: yes. Comment: "We hope that our answer to (the questionnaire) will be of assistance in performing your survey of magnetic-pulse forming. In the interest of evaluating new metal forming processes, we would appreciate receiving a copy of the findings derived from this survey."

7. Classification: Air and Space Vehicles; Acquaintance: laboratory; Interest: considerable; Facility: uncertain. Comment: "Our efforts associated with magnetic pulse forming, to date, have been limited to preliminary experimentation and evaluation to determine potential application to our products. We appreciate the opportunity to participate in this survey and will be pleased to be of further assistance at your request."

Neutral Comments:

1. Classification: Sheet-Metal Configurations; Acquaintance: none; Interest: negligible; Facility: no. Comment: "We are basically a job shop, have no proprietary products, and do contract work primarily, with no long production runs. Have you contacted (five company names)." (Remarks: Long production runs are no criteria for the suitability of MPF. In fact, short runs of different configurations are quite feasible if the total production is great enough to justify the cost of the capacitor bank.)

2. Classification: Sheet-Metal Configurations; Acquaintance: none; Interest: negligible; Facility: uncertain. Comment: (Referring to naming possible parts) "More cost data would be required for analysis."

3. Classification: Sheet-Metal Configurations; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: "We are a job shop. Occasionally we are asked to do some stamping or forming. The job at the time would determine what use we might make of MPF."

4. Classification: Sheet-Metal Configurations; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "We are afraid that we cannot be of much help to you because our operations are largely confined to perforating of steel, metals, and other sheet materials." (Remarks: MPF has considerable promise for forming perforated metals with a minimum of distortion.) (10)

5. Classification: Sheet-Metal Configurations; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "Since we are a custom fabricator of metals, rather than a manufacturer of large volume parts, we believe our interest to be negligible in the Magnetic-pulse forming process." (Remarks: The remarks for No. 1 apply here also.)

6. Classification: Small Machines and Instruments; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comments: "This process is very interesting and looks as if there might be a great application for this type of forming. However, at the present time, the construction of our parts is not adaptable to this method. I would be most interested in hearing the results of this survey and learning of any additional applications for this method."

7. Classification: Small Machines and Instruments; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: "Not applicable to parts manufactured in this plant."

8. Classification: Small Machines and Instruments; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "Although we make energy storage type capacitors of the type used in magnetic-pulse forming equipment, we are not in a position to fill out the questionnaire attached to your letter of March 11. I'm sorry that we can't be of help."

9. Classification: Small Machines and Instruments; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "We have no current experience in Magnetic-pulse forming and do not believe there is any practical application in any of the work that we do here. We do manufacture

or produce small machine parts and stampings for incorporation in certain types of office machines. However, our volume per piece is extremely small and subject to frequent change. We, therefore, do not feel that there is any information which we can give you that would be of any assistance to you in your project." (Remarks: Depending upon the shapes and types of parts involved, MPF would be likely to be advantageous for producing small quantities of a myriad of different parts. For many types of parts MPF could provide simple, easily changed tooling, using the same basic coil for several parts.)

10. Classification: Small Machines and Instruments; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "Please be advised that neither at the present time, or in the near future can we see a need for this technique in our line of manufacturing. We are therefore returning your questionnaire (unanswered)."

11. Classification: Small Machines and Instruments; Acquaintance: literature; Interest: considerable; Facility: yes. Comment: "We are presently investigating the possibilities of this process with (equipment manufacturer)."

12. Classification: Small Machines and Instruments; Acquaintance: none; Interest: considerable; Facility: yes. Comment: (on parts that might be applicable) "None now; would require redesign."

13. Classification: Small Machines and Instruments; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: "Presently looking for applications where the technique will offer cost reduction potentials. One value proposal (for a particular part) now being pursued."

14. Classification: Small Machines and Instruments; Acquaintance: none; Interest: moderate; Facility: yes. Comment: "Process has definite advantages for use in components (cast rotors) to be designed and evaluated in the near future."

15. Classification: Small Stampings and Jewelry; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "While we appreciate your courtesy in writing us, as a company policy, we do not participate in surveys of any type. For this reason, we regret that we cannot be of assistance to you in this instance."

16. Classification: Small Stampings and Jewelry: Acquaintance: literature; Interest: negligible; Facility: uncertain. Comment: "Cost of equipment to form relatively large areas at high pressures (such as required in coining or embossing) is too great in relation to apparent advantages over conventional press methods." (Remarks: This comment is valid with respect to solid parts. However, experience with MPF on parts formed from sheet indicate that it has advantages for coining or embossing, even over large areas.)

17. Classification: Small Stampings and Jewelry; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: (on parts that might be applicable) "None - but have designed parts not capable of manufacture by existing press techniques. While our interest is at the moment only superficial, we do have to keep abreast of such developments."

18. Classification: Tubing Configurations; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "Our principal activity in this division is the production of primary tubing with very limited activity in the fabrication field. Our experience to date on this subject is quite limited and I do not believe we can furnish any information of help to you at this time as solicited in your questionnaire. Accordingly, we are not completing your questionnaire but keeping your information as a reference should this matter come up at some future date or through some customer who does fabrication work."

19. Classification: Tubing Configurations; Acquaintance: literature; Interest: considerable; Facility: uncertain. Comment: (For manufacturing bellows and ball joints from heat-resistance alloys) "we use hydraulic presses up to 500 tons with special long stroke. Also require up to 5,000 psi bulging pressure. Our parent company is interested in the application of swaging ferrules over plastic hose fittings."

20. Classification: Tubing Configurations; Acquaintance: none; Interest: moderate; Facility: yes. Comment: "Perhaps certain types of flexible metal sections could be made by this method. We have no projected or actual cost data useful to this survey."

21. Classification: Large Machines; Acquaintance: laboratory; Interest: moderate; Facility: no. Comment: "We have pursued the possibilities in the use of the magnetic pulse technique of forming with machine tool manufacturers. However, based on our evaluations and vendor recommendations we find that this process does not lend itself to our type of production with its present limitations."

22. Classification: Large Machines; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: "Present manufactured parts do not appear applicable to this process."

23. Classification: Large Machines; Acquaintance: literature; Interest: moderate; Facility: no answer. Comment: "We have been in contact with (equipment manufacturer) and we have witnessed demonstrations of their equipment and at the present time we see no application for this type of operation within the scope of our manufacturing activities. However, we

would like to keep up-to-date on any technologies and if anything further develops, we will be glad to hear from you."

24. Classification: Large Machines; Acquaintance: none; Interest: negligible; Facility: no. Comment: "I did check the matter through with our engineer, and neither he nor I can think of anything we now make that would fit this method. Our interest really is negligible."

25. Classification: Large Machines; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: (with respect to extent of interest) "This only if substantial new developments occurred. At the present stage is of no value to us."

26. Classification: Large Machines; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "We see no use for this equipment in our plant at the present time. The reason for this is that we are a contract engineering organization, usually building one of a kind equipment, and it seems to us that the magnetic-pulse forming technique would not apply in our case, so we are notifying you of this, but are not returning the questionnaire you sent us."

27. Classification: Air and Space Vehicles; Acquaintance: none; Interest: moderate; Facility: yes. Comment: "Do not believe we have any parts which could be advantageously formed by the MPF process. Our AZ31 magnesium components are hot formed, and consequently designed to lower allowable because of strength losses from heat. If the MPF process can accomplish the same degree of deformation without application of heat, the process may then have some advantage."

28. Classification: Air and Space Vehicles; Acquaintance: literature; Interest: moderate; Facility: yes. Comment: "Our experience does not entitle us to comment with any authority. We have studied both explosive and magnetic-pulse forming sheet metal parts but have not reached the experimental stage."

29. Classification: Air and Space Vehicles; Acquaintance: production; Interest: considerable; Facility: yes. Comment: "Very small 110V source used — charge in 15 sec. Equipment used for large quantity of EDF (Electric Discharge Forming) parts. No material cost applies. Small amount of wire and tape used. Lab equipment in use to make production schedules (9600 joule). Production outfit to be set up in June - 25,000 joule."

30. Classification: Air and Space Vehicles; Acquaintance: literature; Interest: moderate; Facility: yes. Comment: "In reviewing our answer, you will note that we have marked a number of questions as answers not available (N/A). Because essentially similar potential applications spread across a number of specific situations where varying methods and equipment are used, we were unable to select one piece of equipment or one method as necessarily typical of a means of producing these kinds of parts under all circumstances."

31. Classification: Air and Space Vehicles; Acquaintance: production; Interest: considerable; Facility: yes. Comment: "The principles relating to this method of capacitor discharge high energy forming have been under study for approximately three years in (Company's) Manufacturing Research Department, with interest toward its ultimate in-plant use. Laboratory-wise, the phenomena has been used to blank, shear, draw-form, bulge and swage aluminum and steel components. In addition, we have formed a production lot of eleven 40" diameter 2014 domes. This part can be formed at lower labor cost on a drop hammer but tooling and equipment costs are higher for the drop hammer. Principle advantages of magnetic forming for part manufacture appear to lie in: 1. short runs where reduced tooling cost offsets higher labor cost, 2. instances where equipment amortization cost offsets higher labor cost, or 3. parts which dimensionally exceed existing press capacity. The latter appears to be an area of great potential for the magnetic forming process. We have a 155,000 joule facility for capacitor discharge metal forming and therefore, look forward to the results of your survey with interest." (Remarks: It is interesting to contrast this comment with those that expressed the opinion that MPF was not compatible with their short-run production requirements.)

32. Classification: Air and Space Vehicles; Acquaintance: laboratory; Interest: considerable; Facility: yes. Comment: "Trial pieces run on (equipment manufacturer's) machine. Further development required. Fine possibility for future applications to (our) parts."

33. Classification: Air and Space Vehicle; Acquaintance: literature; Interest: moderate; Facility: uncertain. Comment: "Manufacturing application (bellows assembly) would be directed toward opening part tolerances yet holding a tight assembly set to facilitate welding of bellows to end plates."

34. Classification: Air and Space Vehicles; Acquaintance: laboratory; Interest: considerable; Facility: no. Comment: "The only parts which appear to lend themselves to possible magnetic forming, also require the use of coaxial cables and split coils, both of which have not been accomplished according to (equipment manufacturer). We have made some experimental parts on the

(manufacturer's) machine; however, we cannot justify a machine on cost savings until they come up with split coils and co-axial cables." (Remarks: The problem with split coils is one that needs further research and development. The comment about co-axial cables is hard to understand, however, because such cables are already in use in at least two installations within the Air and Space Vehicle classification.) **(11, 14)**

35. Classification: Air and Space Vehicles; Acquaintance: literature; Interest: considerable; Facility: uncertain. Comment: "The type of forming described in the subject questionnaire is known in theory to our Manufacturing Research and Development Group through study of available literature and industry contacts. It has been placed in our backlog for future evaluation. Due to the expense of initial power units and alternate methods available for forming applicable parts, this has not yet been put on active status. For this reason most of the answers to the questionnaire are very general in nature except to note that we are interested in any information we may receive on the subject."

36. Classification: Air and Space Vehicles; Acquaintance: literature; Interest: moderate; Facility: yes. Comment: "Cost data would be difficult, if not impossible to correlate, hence would be of no value. Interest would be dependent on type of equipment required, cost, and rate of return on investment. Magnetic Pulse forming requires a very large bank of capacitors, similar to that required for capacitor discharge forming. Restricted areas with electrical safety device protection, especially with respect to grounding will be required. We understand there is a shock wave problem similar to that of explosive or capacitor discharge forming."

37. Classification: Air and Space Vehicles; Acquaintance: laboratory; Interest: considerable; Facility: yes. Comment: "The (name) Branch is currently developing MPF for the parts described. Present forming methods are available for each, however, comparison to M. P. F. cannot be made since these parts are not actually in production at this time. Experience to date indicates that lower tool costs, die costs and fewer steps in fabrication would be required for M. P. F. over our conventional methods."

38. Classification: Primary Metals; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "Our company has no interest in the magnetic-pulse forming process as it may be applicable to our operations at the present time and, therefore, we beg to be excused from filling out the questionnaire which you enclosed with your letter."

39. Classification: Primary Metals; Acquaintance: literature; Interest: considerable; Facility: yes. Comment: (on parts that might be applicable) "None - considerable interest from our customers for a wide variety of products."

40. Classification: Unclassified; Acquaintance: literature; Interest: negligible; Facility: uncertain. Comment: "Possibly some of our components could be redesigned to use this procedure if economically sound."

41. Classification: Plate and Structural Configurations; Acquaintance: none; Interest: moderate; Facility: no. Comment: "I am writing to inquire if there are any magnetic pulse forming units available for demonstration. I would like to attempt to show some of our manufacturing management the operation of such a unit on a demonstration basis. Can you suggest some one who is either working on or manufacturing such units." (Remarks: This respondent was referred to an equipment manufacturer.)

42. Classification: Nonmetallic Products; Acquaintance: no answer; Interest: no answer; Facility: no answer. Comment: "I have read the information sheet which you enclosed with your information sheet with interest. While I am sure that I should be better informed about this process than I am, it would only be under the heading of general information in the metal forming field rather than something that I believe would be applicable to our operations here. However, many of our customers in the powder metallurgy field are parts manufacturers and I believe that this highly specialized forming method may be applicable in the forming of very complex shapes that possibly could not be made by the simpler mechanical powder pressing techniques. It appears that the production rate is governed by the charging time of the capacitor bank (given as 12 per minute) which is low for mechanical press forming but might be considerably faster than hydrostatic forming rates, for example. I am sure you will understand our inability to give you any cost information or to supply printed information sheets dealing with this subject. In view of the fact that we have gone this far, I am sure that we would appreciate being informed of the results of your survey." (Remarks: The capacitor charging time given was conservative and does not necessarily restrict production rates. Capacitors may be charged at rapid rates with special techniques (14). Another method for achieving high production rates is to use several capacitor banks connected to the coil through a timing switch that discharges each bank of capacitors in succession (9). This method combines longer capacitor life with an increased rate of production. Of course, resorting to multiple capacitor banks increases the capital cost of the equipment.)

Personal Interviews

It was hoped that detailed discussions with several manufacturers would result in the acquisition of some cost comparisons that would be of great value in themselves and, in addition, aid in the interpretation of the cost information supplied on the returned questionnaires. Interviews were held with various personnel from seven different manufacturers before this hope was abandoned. It was found that the lack of sufficient information on the details of MPF capabilities and limitations precluded the possibility of obtaining estimated value analyses that would not involve an amount of study and computation far beyond the scope and funding of this project. Even if such detailed analyses had been made, it would have been necessary to place an unwarranted degree of confidence in several unproved assumptions. Therefore, the personal interviews were discontinued after it was determined that they were not yielding the desired information.

The interviews did result in one impression that is pertinent to the survey. This impression was that interest and enthusiasm for the process increases the more it is discussed and considered from the standpoint of its several unique characteristics. It was found that most interviewees began the discussion with an attitude of moderate interest in a new process about which they should keep informed. At the conclusion of the interviews the attitude had changed to one of a high degree of interest and a desire for sufficient information to evaluate MPF for the manufacture of specific parts and assemblies produced by the company concerned.

DISCUSSION

It is obvious from the answers received on the questionnaires and from the conflicting comments made by many of the respondents that industry in general has been unable to properly evaluate the many promising characteristics of MPF because of a lack of sufficient information. Although a greater amount of literature has accumulated than might be expected for such a recently developed process, it has not supplied the basic information needed to make cost analyses with sufficient confidence to determine whether investments in equipment and development programs would prove profitable. Formulas necessary for coil and circuitry design, as well as for the calculation of the pressures obtainable, have been reported (5, 14). However, inertial and other effects also have a large influence on forming characteristics; consequently, the calculated pressures are more valuable for determining the required strength of the coil material than they are for determining the extent of workpiece deformation.

Although the power equipment for MPF is costly, it is comparable to the cost of conventional mechanical and hydraulic presses (14). Therefore, first cost will not deter acceptance of the process when enough information on operational characteristics becomes available. The type of information that is lacking for evaluation purposes is not that of theory and mathematical analysis but that of the basic parameters for practical application. Although these basic parameters will slowly evolve from developmental efforts with individual parts, the sacrifice in time may place American industry in a detrimental competitive position with respect to foreign industry. It was pointed out in a recent seminar on high-energy-rate-forming methods that the sale of magnetic-pulse forming equipment is considerably more active in Europe than in the United States.

It must be realized, of course, that the determination of basic parameters will not preclude the necessity for considering almost every prospective application as a separate entity on which some experimental work will be necessary before the application can be successfully accomplished on a production basis. However, the same situation applies to conventional mechanical or hydraulic presses. It is seldom that a new configuration with any significant degree of complexity can be placed in production without some rework of the original die design and some adjustment in the proposed manufacturing procedures. With some knowledge of the basic parameters of the MPF process, manufacturers will have a basis for determining whether it will be worthwhile for them to initiate development work and for estimating the cost of such development.

Stated simply, the information needed includes the following:

1. Determination of the relationship between joule energy level and the extent to which materials of various types can be formed under otherwise identical conditions.

2. Determination of the relationship between joule energy level and the extent to which various wall thicknesses of given materials can be formed under otherwise identical conditions.

3. For cylindrical shapes, determination of the hoop-stress effects; that is, the relationship between joule energy level and starting diameters under otherwise identical conditions.

4. Determination of special characteristics such as the ability to:

a. Form shapes from flat sheet or plate.

b. Faithfully reproduce threads, lettering, or decorative designs when forming against a die or mandrel.

c. Form metals and reproduce surface patterns when formed against soft and nonmetallic die or mandrel materials.

d. Punch holes in metals through soft die materials.

e. Form metals with eccentrically shaped coils.

f. Form nonmetallic or difficult metallic materials by means of metallic shims, foils, or other types of conductive coatings.

Because of the absence of a single criterion for determining the significance of the results from the survey, several different interpretations are possible. For this reason, the results have been presented in sufficient detail to allow individual readers to make their own interpretation if they disagree with that made herein.

The summarized results in Figures 6 and 7 indicate that the impact of MPF on industry has been small up to the present time. Only "moderate to negligible" interest in the process is shown by the total response and most of the industry classifications. Only two classifications, TUBING CONFIGURATIONS and AIR AND SPACE VEHICLES, indicate "moderate to considerable" interest, and these two classifications are in the fields in which most of the MPF activity has been concentrated. This distribution and that in Figure 7 point out that interest is most prevalent among those who are best acquainted with the process. It is significant to note that the location of the total response in the "Moderate to Negligible" interest category is probably caused by the overwhelmingly large number of respondents that reported no previous acquaintance or only literature acquaintance with the process. Again, the lack of information upon which to base an evaluation of MPF potential is emphasized.

The desire for more information is also reflected by the distribution of the answers to question 6 (pertaining to the establishment of a NASA facility). It is shown that, in general, the industry categories and the total response show a greater level of enthusiasm for the establishment of the experimental facility than for the process itself. Again, those industry classifications and those respondents best acquainted with the process gave the most support to the establishment of an experimental facility. It is felt that these results indicate that the establishment of a NASA-sponsored experimental facility would facilitate

the exploitation of magnetic-pulse forming by industry.

CONCLUSIONS

1. The magnetic-pulse-forming process has many potential applications that would be advantageous to American industry, but most of these applications have not been realized.

2. More information is needed on the basic practical parameters of the process, especially with respect to materials, blank thicknesses, and size restrictions, before industry can adequately evaluate its utility in comparison with conventional forming methods.

3. Sufficient interest and support have been shown by industry to indicate that a NASA-sponsored experimental facility in an independent laboratory would be useful in serving industrial needs for research, development, and consultation on the technology and economics of magnetic-pulse forming. Such a facility would undoubtedly accelerate industrial exploitation of magnetic-pulse forming.

Birmingham, Alabama
June 5, 1963
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APPENDIX

Letter explaining the survey
Information sheet on Magnetic-Pulse Forming
Questionnaire
Summary of Cost Information

Southern Research Institute

2000 NINTH AVENUE SOUTH
BIRMINGHAM 5, ALABAMA

Gentlemen:

We seek your help in obtaining for the National Aeronautics and Space Administration certain facts pertaining to the potential application of the magnetic-pulse forming technique in industry. If these facts indicate sufficient potential for the process, the Applications Office of NASA may establish an independent research and development facility that will work with industry to adapt the magnetic-pulse technique to commercial manufacturing practice. Success in the establishment of such a facility may indicate the best means for transposing other advances in space technology to general use.

Magnetic-pulse forming is a recently developed process with several unique features that should prove advantageous in the forming of many types of parts. Development work by the Manufacturing and Engineering Division of the George C. Marshall Space Flight Center of NASA has produced evidence to support the belief that the process may be superior to other forming methods in terms of tooling and operating costs. For the benefit of those who are unacquainted with this forming process, we have enclosed an information sheet that briefly describes the principles of magnetic-pulse forming and illustrates several actual and prospective applications.

In order to obtain the required information, Southern Research Institute, under NASA Contract No. NAS8-5021, is conducting a survey of approximately 500 companies by means of the enclosed one-page questionnaire. We request that you or an appropriate member of your organization complete the questionnaire and return it to us in the envelope provided. In order to conserve your valuable time, we have composed the questionnaire to require only check marks, figures, or simple single-word answers. If you cannot supply exact information, we would still appreciate receiving your best estimates, and even partially completed questionnaires will be valuable to us.

We realize that some of the information requested, particularly that pertaining to costs and production rates, is of confidential nature. We assure you that all such data will be combined and presented in a manner that will preclude its identification with any particular company or individual. If you still hesitate to release actual cost figures, we would welcome this type of data expressed as a percentage of total direct cost.

Since the time allotted to this survey by NASA is limited, we ask that you return the questionnaire by April 1 to allow sufficient time to compile the results. We and the NASA will certainly appreciate your participation in this survey. If you desire additional information about any aspect of this program or Southern Research Institute, please do not hesitate to request it from us.

Very truly yours,

J. R. Kattus

J. R. Kattus, Head
Metallurgy Division

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INFORMATION SHEET ON MAGNETIC-PULSE FORMING

Magnetic-pulse forming is a relatively new process in the field of high-energy-rate forming methods, which, in general, includes those processes in which the forming operation is completed within several milliseconds or less. Unlike explosive-forming or exploding-wire electrical-discharge forming, magnetic-pulse forming does not require a remote installation or the installation of a water tank. The force used in magnetic-pulse forming is generated when the energy stored in a bank of capacitors is discharged into an air-core coil that is in close proximity to the piece to be formed. The resulting magnetic field induces a current in the workpiece surface adjacent to the coil, and this induced current creates a field in opposition to the coil field. The reaction between the opposing fields acts equally on both coil and workpiece, so that if the coil is adequately restrained, the workpiece is deformed.

It is not necessary that the material to be formed be magnetic. However, it must have relatively high electrical conductivity in order that a large current may be induced in the surface of the workpiece by the pulsed magnetic field. Metals of low electrical conductivity, and even "nonconductors," can be formed by placing a very thin sheet of a highly conductive metal, such as copper or aluminum, between the coil and the workpiece. A current is induced in the thin conductive material, and the resulting force deforms both the conductor and the low-conductivity workpiece. Size restrictions are partly dependent on the size of coil needed to deform the workpiece. For thin-walled tubing, the practical minimum inside diameter is approximately 1/4 in. The maximum size limits are unknown, but existing equipment has deformed parts as large as 4 ft inside diameter. Magnetic-pulse forming is adaptable to many mass production operations. The energy required for forming most parts can be stored (the capacitor-bank charged) in about five seconds, and the forming operation itself is completed within about 50 microseconds.

Both free-forming and die-forming may be done by the magnetic-pulse method. Figures 1 and 2 show typical examples of both types of forming and also show the relationship between the coil, workpiece, and die (if used). In Figure 1, a tube is being bulged by magnetic-pulse free-forming. Here, the coil is inside the tube, and the force generated between the coil and the inner surface of the tube produces the bulge. Since the energy used in magnetic-pulse forming may be carefully controlled, excellent reproduciblity is obtained in free-formed configurations. If desired, the tube or a deep-drawn cylinder) may be formed against a divided restraining die to emboss decorative

engraving or to reproduce nonconcentric and irregular-shaped configurations. Figure 2 shows a tube being swaged on a fitting. In this example, the coil surrounds the workpiece, and the fitting is, in effect, a die that determines the final configuration of the workpiece.

As indicated in these two figures, magnetic-pulse forming is particularly useful in, but not by any means limited to, tube-forming operations. Flat "hammer" coils may be used in sheet-forming operations, such as grooving, coining, and sealing.

In addition to Figures 1 and 2, which show known existing production applications for magnetic-pulse forming, other figures are presented showing applications in development (Figures 3 and 4) and applications that are believed to be feasible after a suitable development effort is made (Figures 5 and 6).

It is impractical to include diagrams or sketches of more than these few representative applications of magnetic-pulse forming. However, reference may be made to the following list of a number of additional applications, some of which represent production items, some, items in development status, and others, possible future applications. It is hoped that this list will serve to stimulate interest in magnetic-pulse forming as an industrial process and help to generate new ideas for its application.

ADDITIONAL APPLICATIONS OF MAGNETIC-PULSE FORMING

1. Pointing (by swaging) of tubing or bar for introduction into drawing dies.
2. Attachment of sleeve or collar on large lock-bolts.
3. Attachment of electrical connectors to cables.
4. Coining—transfer of ornamental die designs.
5. Capping of bottles.
6. Forming contours and designs in metal containers of all sizes. (Shaped cans or metal "bottles.")
7. Flanging of tubing or pipe of various sizes.
8. Cold-welding.
9. Binding of multiple-component assemblies by strapping or enclosing in thin-sheet retaining rings.
10. Circumferential depressions in round solid bars to eliminate or reduce machining.

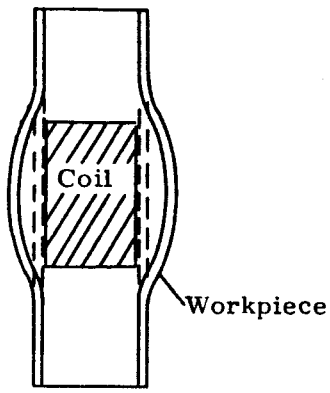

Figure 1. Bulging of tube

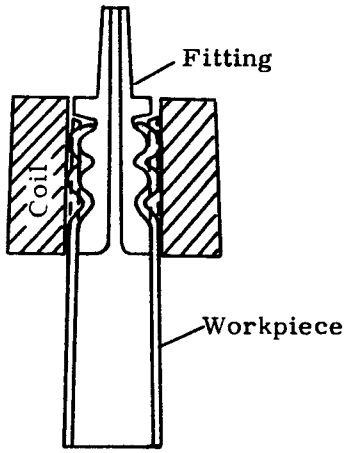

Figure 2. Swaging tube on fitting

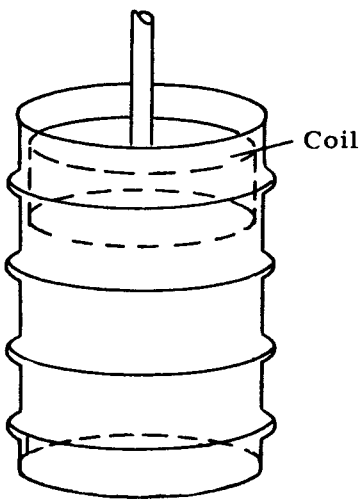

Figure 3. Free-forming of "gyri" stiffeners in large diameter tubing.

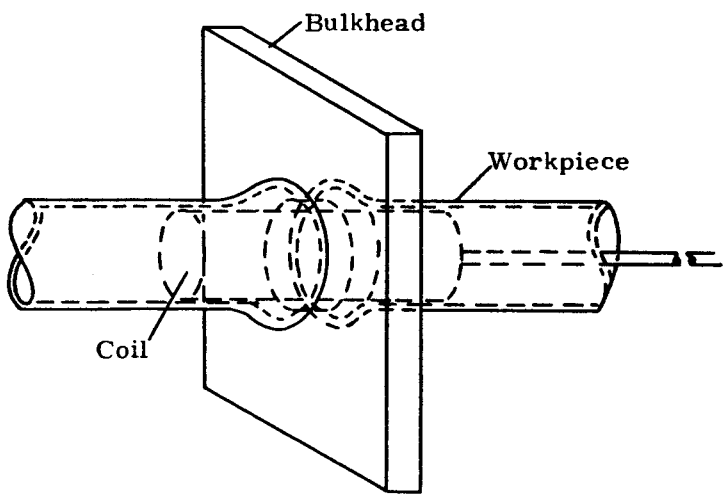

Figure 4. Securing pipe in bulkhead by bulging

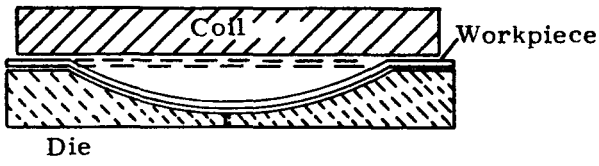

Figure 5. Die-forming a shallow "dish"

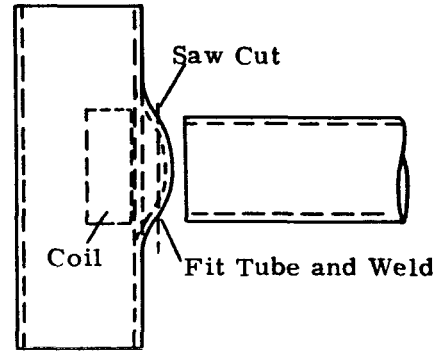

Figure 6. Making "Tee" assembly in large diameter pipe or tubing. Bulge produced by magnetic pulse is cut as shown, and stem is welded on.

SOUTHERN RESEARCH INSTITUTE
2000 Ninth Avenue South
Birmingham 5, Alabama
FA3-6592, Area Code 205

QUESTIONNAIRE

On

Industrial Applications for Magnetic-Pulse Forming

ate Completed: _____ Division: _____

espondent: _____ Company: _____

itle: _____ Address: _____

elephone: _____ _____

What are the primary industry and the primary products of your division or company? (We prefer the terminology used in the STANDARD INDUSTRIAL CLASSIFICATION MANUAL of the United States Office of Statistical Standards.)

Industry: _____ Product: _____

Product: _____ Product: _____

What has been the previous acquaintance of your division or company with magnetic-pulse forming?

☐ Production experience ☐ Lab or pilot plant experience ☐ Literature only ☐ None

Based on your knowledge of the process (or the description in the enclosed Information Sheet), please list any parts made by your division or company for which you believe the magnetic-pulse forming method may be advantageously applied. (If relevant, list parts already being made by M. P. F.)

Name of Part	Type of Metal Used in Part	Average Annual Production Pieces Per Year	Production Rate Pieces per Hour
a.			
b.			
c.			
d.			
e.			

If available, please furnish the following information for the parts listed under Item 3. (If known data cannot be supplied, your estimates would be appreciated).

Present Forming Method	Installed Cost, One Unit, Primary Mfg. Equipment	Total Direct Production Cost Per Piece	Tooling Cost Per Piece	Labor Cost Per Piece	Energy Cost Per Piece
a.					
b.					
c.					
d.					
e.					

To what extent do you think your division or company would be interested in exploring the usefulness of magnetic-pulse forming for your operations?

☐ Considerable Interest ☐ Moderate Interest ☐ Negligible Interest

Do you think your division or company would derive benefits from the establishment of an NASA-sponsored experimental facility to serve industrial needs for research, development, and consultation on the technology and economics of magnetic-pulse forming?

☐ Yes ☐ Uncertain ☐ No

Can you supply additional information on magnetic-pulse forming, particularly as it may apply to your division or company? We shall welcome any comments, information sheets, or brochures you may wish to return with this questionnaire.

Do you wish to be informed of the results from this survey? If so, please check here: ☐

Thank you for your cooperation,

Southern Research Institute

SUMMARY OF COST INFORMATION

General					Forming Data						
Industry Classification	Type of Part	Size of Part	Metal Used	Average Annual Production	Forming Method	Capital Cost One Unit	Production Rate Pcs/Hr	Tooling Cost Per Piece	Labor Cost Per Piece	Energy Cost Per Piece	Total Cost Per Piece
Sheet	Oval & round tank heads		L. C. Steel	2,400	Hydraulic press	$100,000	6		$ 3.50	$	$
Sheet	Bun pans		Tin plate	400,000	Deep drawing	20,000					
	Bun pans		Aluminum	400,000	Deep drawing	20,000					
	Seamless cake pans		Tin plate	75,000	Shallow drawing	7,000					
	Seamless cake pans		Aluminum	75,000	Shallow drawing	7,000					
Sheet	Bun moulds	22 Gage	Tin plate	125,000	Draw press	55,000	650		0.03	0.001	0.10
	Cake cups	26 Gage	Tin plate	2,000,000	Draw press	8,500	1,800		0.01	0.0002	0.03
	Cake pans	26 Gage	Tin plate	600,000	Draw press	15,000	950		0.02	0.0002	0.06
Sheet	Metal case for money register	18" W x 14" D x 20" H 16 Gage	Stainless Steel	100	Shear, brake, roll, weld, grind, polish			5.00	70.00	1.00	80.00
Sheet	Light reflectors		Alzak Al	60,000	Spinning		10		0.40	0.04	0.56
					Drawing				0.10	0.02	0.16
Sheet	Lawnmower decks	14 Gage	C.R. Steel	100,000	Straight side draw press	85,000	250		0.145		
	Drum heads	18 Gage, 55 gal	C.R. Steel	240,000	Straight side draw press	85,000	270		0.025		
	Cabinet drawer pans	24 Gage, 15"	C.R. Steel	20,000	Straight side draw press	85,000	250		0.089		
	Heater ends	22 Gage	C.R. Steel	25,000	Straight side draw press	40,000	300		0.071		
	Chair base legs	18 Gage	C.R. Steel	250,000	Straight side press	18,000	325		0.035		
Sheet	Textured sheets		Steel	250,000	Rolling—male & female dies	175,000		0.10	0.50		0.70
			Aluminum	250,000	Rolling—male & female dies	175,000		0.10	0.50		0.70
Sheet	Precision parabolic & hyperbolic antennas		Aluminum	200	Vacuum, pressure, & heat			$500.00 to $20,000.00	$500.00 to $10,000.00		$1,000.00 to $30,000.00
SM&I	Bracket		5052-H32 Al	200	Punch & Die		15	0.20	0.28		0.50
	Strap		5052-H32 Al	1,300	Punch & Die		60	0.02	0.06		0.08
	Bracket		1/2H Brass	2,500	Punch & Die		20	0.05	0.20		0.26
	Shell		Soft Brass	300	Punch & Die with air cushion		40	0.09	0.11		0.12
	Formed Washer		1/2H Brass	400	Punch & Die		120	0.04	0.04		0.05
SM&I	Floor tool handles		Steel	2,000	Brazing and expanding	1,200					
			Aluminum	2,000	Brazing and expanding	1,200					
	Bushings & couplings		Steel	5,000	Expanding and machining	20,000					
			Aluminum	5,000	Expanding and machining	20,000					
SM&I	57 Series hood	22 Gage	C.R. Steel	1,196,000	Progressive die	28,000	5,000		0.00045	Nil	0.0486
SM&I	Primer tube		Brass	5,000	Joined by silver solder		300		0.40	0.02	0.50
	Fitting		Brass	10,000	Joined by silver solder		300		0.20	0.02	0.30
SM&I	Coupling ring*				Screw machine & chucker	7,500		1.05	5.20		7.35
					Magnetic-pulse forming	15,000		0.10	0.80		1.10
SM&I	Relay cases		Armco Iron	100,000	Press	1,000	180		0.60		
	Instrument panels		Aluminum	1,000	Press & castings		2				
SM&I	Platen core 445130		Al (3003)	250,000	3 separate forming operations	17,000		Nil	0.05233		0.07098
	Platen core 445350		Aluminum	250,000	3 separate forming operations	17,000		Nil	0.04466		0.05947
SM&I	Contact switch blades		Phos. Bronze	5,000,000	Punch press	2,000	600	Nil	0.01		0.02
			Be Copper	5,000,000	Punch press	2,000	600	Nil	0.01		0.02
	Actuating blades		Steel	1,000,000	Punch press	2,000	600	Nil	0.01		0.02
SS&J	Bellows convolutions		Phos. Bronze	75,000	Hydraulic pressure	8,000	100	Nil	0.02		0.13
	Bellows convolutions		Stainless steel	75,000	Hydraulic pressure	8,000	100	Nil	0.02		0.13
	Switch case		Stainless steel	250,000	Mechanical blank & form	15,000	500	0.0005	0.015		0.08
	Switch shell (tubing)		Brass	500,000	Die formed & broached	7,500	1,000	0.0002	0.0075		0.065
	Switch shell (tubing		Stainless steel	500,000	Die formed & broached	7,500	1,000	0.0002	0.0075		0.065
Tubing	Buick exhaust pipes	2 1/2" x 0.061"	Steel	45,000	Punch press with rubber expanding	6,000	100	0.005	0.025		0.07

SUMMARY OF COST INFORMATION (Continued)

General					Forming Data						
Industry Classification	Type of Part	Size of Part	Metal Used	Average Annual Production	Forming Method	Capital Cost One Unit	Production Rate Pcs/Hr	Tooling Cost Per Piece	Labor Cost Per Piece	Energy Cost Per Piece	Total Cost Per Piece
Tubing	Wrought tees	1/2"	Copper	3,000,000	Hydraulic	$ 62,400	923	$ 0.0036	$ 0.0026	$	$ 0.0122
Tubing	Containers		Steel		Mechanical expansion	10,000	450		0.01	0.01	
	Drums		Steel		Mechanical expansion	35,000	1,700		0.01	0.01	
Tubing	11662 venturi		AM 350	50	Weld & spin				16.00		22.00
	11868-33 liner		321 SS	100	Hydraulic bulging				50.00		90.00
Tubing	Pointing ends of tubing		Brass	3,000,000	Squeeze pointer & rotary swager	23,000	50		0.10		0.24
	Expanding ends of tubing		Brass	10,000	Stripper	10,000	280		0.018		0.043
Tubing	Pointing ends		Carbon steel	1,000,000							
			Alloy steel	1,000,000	Swaging & press pointing	5,000	100	0.010	0.030	0.002	0.042
			Stainless steel	1,000,000		15,000	200				
			Nickel	1,000,000							
Tubing	Heat transfer tubes		Steel	1,000,000	Swaging				0.20		0.60
			Copper								
	Drip pans		Steel	25,000	Conventional forming				0.50		2.00
			Aluminum								
LM&E	Appliance panels		Steel	100,000	Dies and draw presses	10,000 to 50,000	100	0.01	0.015		0.035
A/c & Space	Venturi tube*	3.4" O.D. x 0.035" wall	6061-0 Al alloy	100	Magnetic-pulse forming	11,000	2	0.30	2.50		3.20
	Control rod*		Al alloy	280	Magnetic-pulse forming	11,000	6	0	0.90		0.90
	Nose wheel stabilizer*		Al alloy	350	Magnetic-pulse forming	11,000	6	0	0.90		0.90
A/c & Space	Rocket engine fuel tubes		347 SS	50,000	Swage						1.00
	Rocket engine fuel tubes		Inconel	50,000	Swage						1.00
A/c & Space	40" Dia. dome		2014 Al	10	Drop hammer	50,000	0.5		2.00		
	Domes over 100" dia.		Al alloys		None—beyond press capacity	200,000					
	Port flaring		Aluminum		Ball draw operations	30,000			10.00		
	Port flaring		Steel		Ball draw operations	30,000			10.00		
	Corrective forming		Aluminum		Hand operations						
	Swaging		Aluminum		Punch press	15,000			1.00		
A/c & Space	Tubing	2.0" O.D. x 0.058" x 19.5"	2024-T3 Al		Swage to 1.743" O.D.	8,000	5	Nil	0.60	0.035	1.20
	Tubing	1.0" O.D. x 0.035" x 35.37"	2024-T3 Al		Swage to 0.821" O.D.	8,000	12	Nil	0.25	0.015	0.50
	Tubing	1.5" O.D. x 0.028" x 6.6"	6061-O Al		Bead one end	8,000	44	Nil	0.07	0.001	0.14
	Tubing	2.0" O.D. x 0.035" x 115"	6061-T6 Al		Bead both ends	8,000	4	Nil	0.75	0.045	1.50
A/c & Space	P/N 136048 tube		Aluminum	500	Logansport forming machine	1,000	240	Nil	0.056	0.01	0.015
	P/N 136501 tube		Aluminum	15,000	Logansport forming machine	1,000	240	Nil	0.056	0.01	0.015
	P/N 134079 tube		Aluminum	15,000	Logansport forming machine	1,000	240	Nil	0.056	0.01	0.015
	P/N 134080 sleeve		321 SS	35,000	Lathe	3,000	120	Nil	0.115	0.01	0.030
	P/N 145334 ball joint		N-155 alloy	3,000	Hydraulic press	70,000	40	1.00	0.345	0.02	0.090
Nonmetallic	Tube end for hose assembly	3/4" Dia.	Steel	500,000	Swaging	20,000	300	0.2	23.0%	0.022	
	Crimped hose end (auto air cond.)	1 1/8" Dia.	Steel	500,000	Crimping	18,000	300	0.2	3.6%	0.022	
	Hose end (auto fuel & oil)	5/8" Dia.	Brass	1,000,000	Crimping	5,000	300	0.1	6.6%	0.011	
	Hose end (hydraulic)	1" to 2" Dia.	Steel	2,000,000	Crimping	18,000	350	0.2	6.0%	0.019	

* Contains magnetic-pulse forming data.